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Rosatom State Atomic Energy Coproration & National Research Nuclear University “MEPhI”

Course: Fundamentals of Modern Russian designed NPP with VVER 1200 power reactor

Module 4: Design Solutions of reactor auxiliary system and turbine part

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Reviewed by:

Based on materials prepared by: Rosatom Technical Academy (RosatomTech)

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Fundamentals of Modern Russian designed NPP with VVER 1200 power reactor

4. Design Solutions of reactor auxiliary system and turbine part

The terminal training objective of the fourth part of the course is to identify the technological features of auxiliary systems and the secondary circuit. The corresponding training objectives are:

- to describe the characteristics of the steam turbine;
- to discuss the main systems of the secondary circuit of Modern Russian designed NPP with VVER 1200 power reactor;
- to describe spent fuel handling system of Modern Russian designed NPP with VVER 1200 power reactor.

The following topics will be covered in this part of the course:

1. Main systems of the primary circuit;
2. Operation of the auxiliary systems under normal operating conditions;
3. Turbine island;
4. Handling of spent nuclear fuel.

4.1. Main systems of the primary circuit

Reactor auxiliary systems

As described in the third part of the course, two coolant cycles are used for VVER plant, the primary and secondary coolant circuits. The main equipment of the primary circuit consists of reactor, main circulation pump, and steam generator. In the secondary circuit, there are steam generator, steam turbine, condenser, and feedwater pump. For normal operation and anticipated operation occurrences, a normal operation system is necessary. This system is called the ***auxiliary reactor operation system*** for NPPs. There is a long list of components in this system for VVER reactors (e. g. for VVER-1200) presented in Table 4.1.1.

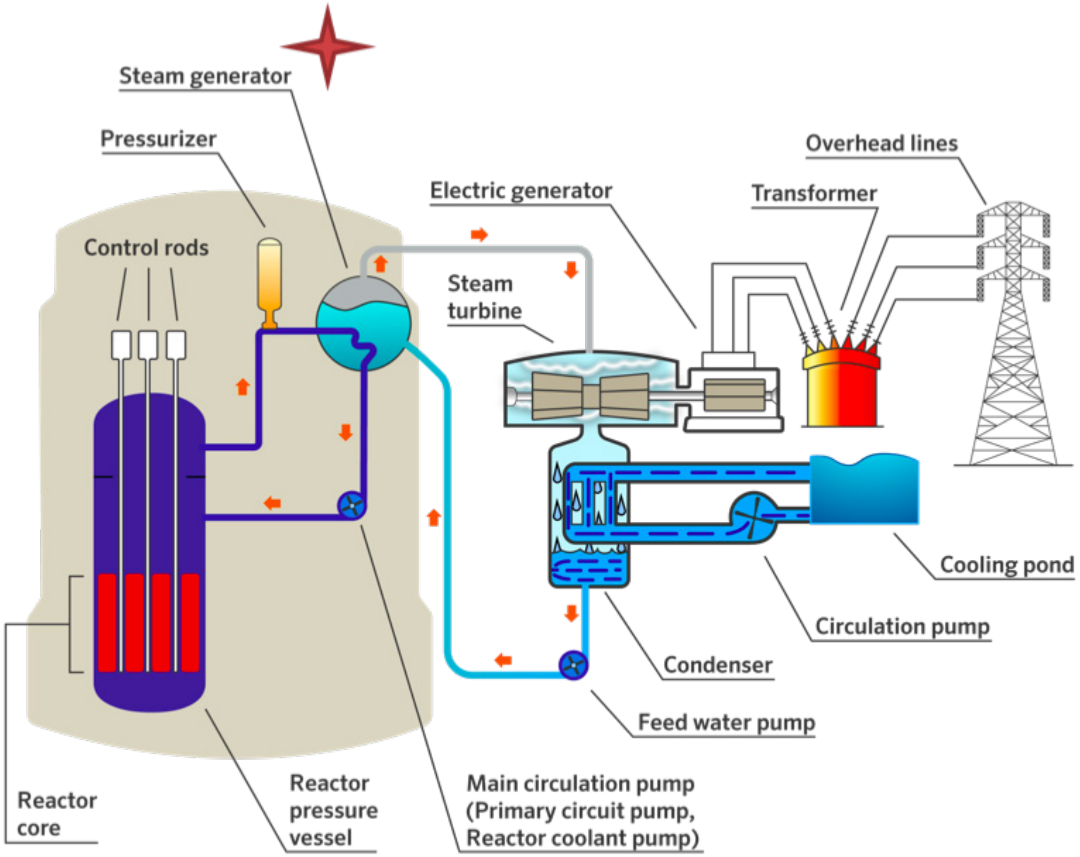

***Figure 4.1.1.** A simplified flow diagram of two-circuit NPP.*

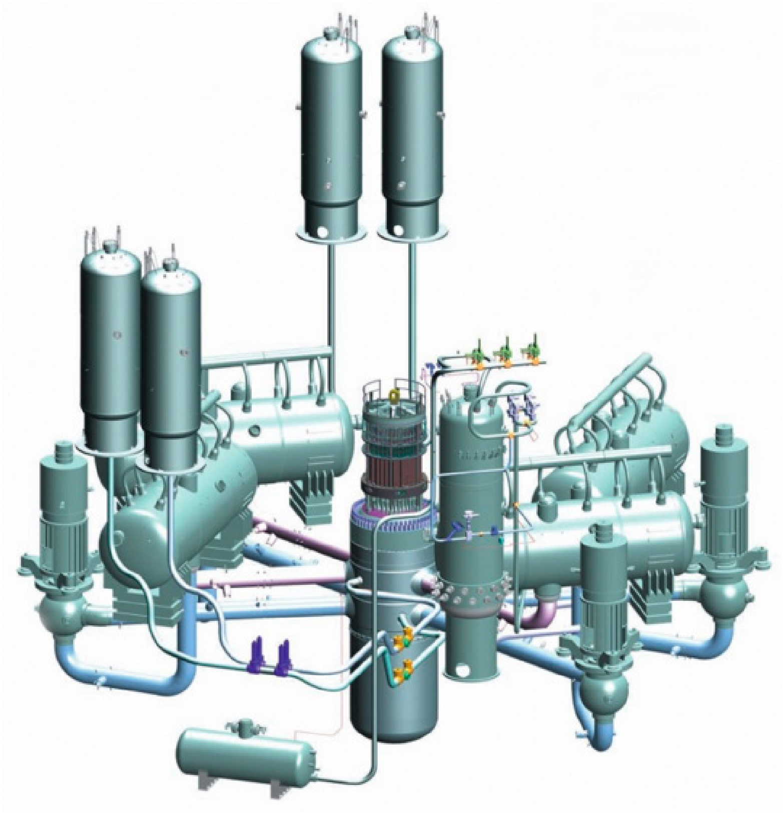

Figure 4.1.2. Primary circuit auxiliary systems.

- ***Primary circuit auxiliary systems*** are designed for normal operation conditions and in case of anticipated operational occurrences.
- ***Normal operation*** of the NPP is operation of the plant within the limits and under the conditions specified by the design.

Auxiliary system	KKS denotation
Makeup and boron control system	KBA
Coolant storage system	KBB
Pure condensate supply system	KBC-1
Primary coolant purification system	KBE
Demineralized water supply system	KBC-2
RCP sealing water system	JEW
Reactor building equipment drainage system	KTA
High pressure nitrogen system	KRJ
Low pressure nitrogen system	KRK
Primary coolant treatment system	KBF
Hydrogen burning system	KPL1
Radioactive gas treatment system	KPL2
Chemicals preparation and supply system for maintaining primary coolant chemistry	KBD-1
Vent system of reactor building equipment	KTB
Reactor coolant leakage collection system	JET

Table 4.1.1. *Denotation of main auxiliary process systems of the primary circuit according to The Identification System for Power Stations (KKS).*

The abbreviations in the right column of Table 4.1.1, such as LCU and KBB, are The Identification System for Power Stations (KKS) codes. KKS codes were developed in Germany for thermal power plants to identify different systems, components, and elements of power plants. Abbreviations of this type are used for all components of NPPs as well. In this case, abbreviations for all systems of Modern Russian designed NPP with VVER 1200 power reactor are identified, which are in line with system identification for all NPPs.

For example, auxiliary systems can have the following functions:

- *Makeup and boron control system (KBA):* controlling the concentration of boric acid in the primary circuit, adding and removing coolant.
- *Coolant storage system (KBB):* storing coolant of the primary circuit when adding or removing coolant.
- *Pure condensate supply system (KBC-1):* supply of pure condensate into the primary circuit in the identified operation categories.
- *Primary coolant purification system (KBE):* cleaning and treatment for the primary circuit coolant.

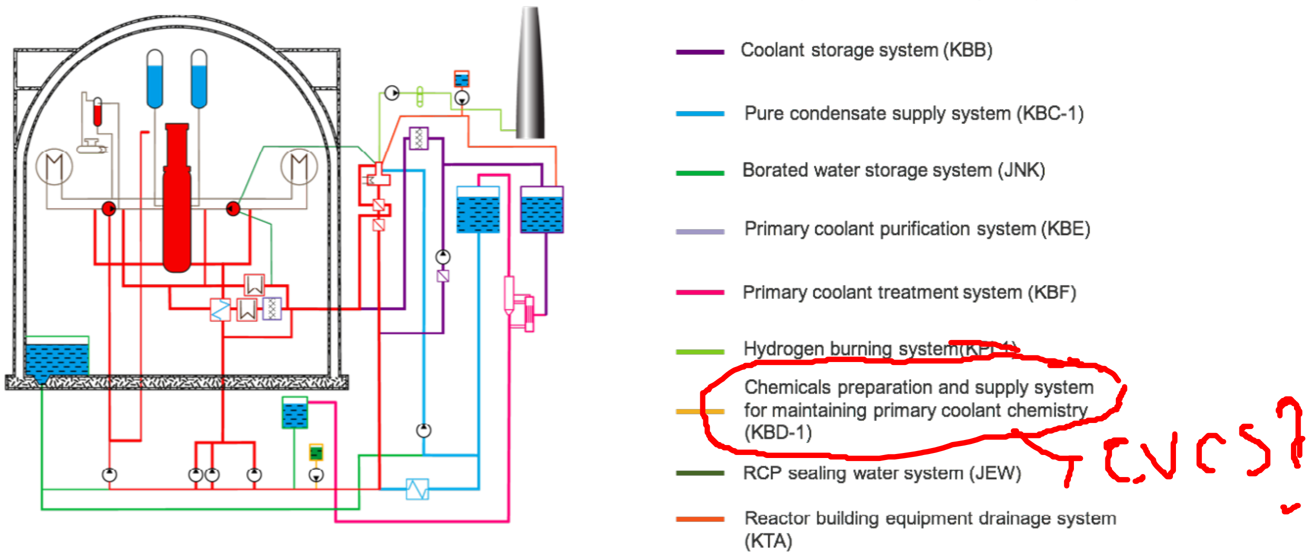
Makeup and boron control system (KBA)
Coolant storage system (KBB)
Pure condensate supply system (KBC-1)
Borated water storage system (JNK)
Primary coolant purification system (KBE)
Primary coolant treatment system (KBF)
Hydrogen burning system(KPL-1)
Chemicals preparation and supply system for maintaining primary coolant chemistry (KBD-1)
RCP sealing water system (JEW)
Reactor building equipment drainage system (KTA)

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Figure 4.1.3. *General arrangement of auxiliary systems interacting with the primary circuit.*

Auxiliary systems of the primary circuit ensure operation of the reactor plant under the following normal operating conditions:

- **I**: Primary circuit filling. When an NPP and all its equipment have been assembled, it should be possible to fill the primary circuit.
- **II**: The second mode is reactor pressure heating (up to 135 °C), hydraulic tests, and heating up to the hot condition. A system is necessary for heating up, to control the speed of heating, and to provide hydraulic tests.
- **III**: Reaching the minimum controlled power level and increasing power to the nominal power level. A system is needed for, for example, removing boric acid from the primary circuit and adding clean condensate, which results in added positive reactivity and increased level of power, so a changed neutron power of the reactor core.

- **IV**: Steady-state conditions and unit power change (maneuvering). NPP are operated at the nominal level of power; however, for some reasons, e. g. requirements from the electricity grid operators to reduce the level of power during nighttime and increase the level of power during daytime, the level of power could be changed. Power consumption varies on different days, months, and years. Based on that for some NPPs, such as Modern Russian designed NPP with VVER 1200 power reactor, there are strict rules about the possibility to have maneuvering regimes. For example, during daytime the power level is to be 100% and during nighttime—50%. So, a normal operation system that allows these changes is required.
- **V**: Reactor cooldown from hot condition to the cold one and maintenance outage (draining and equipment unsealing). Systems are needed to support these activities.
- **VI**: Equipment emptying. Some of the equipment of the primary circuit occasionally needs to be emptied; all coolant needs to be removed for cleaning, deactivation procedures, or for maintenance and repair activities.

In case of anticipated operational occurrences (AOO), for example NPP blackout or small leakage, a normal operation system should be available to compensate for these occurrences and come back to normal operation conditions. The following section examines these conditions and identifies the corresponding systems used in each condition.

4.2. Operation of the auxiliary systems under normal operating conditions

Primary circuit filling

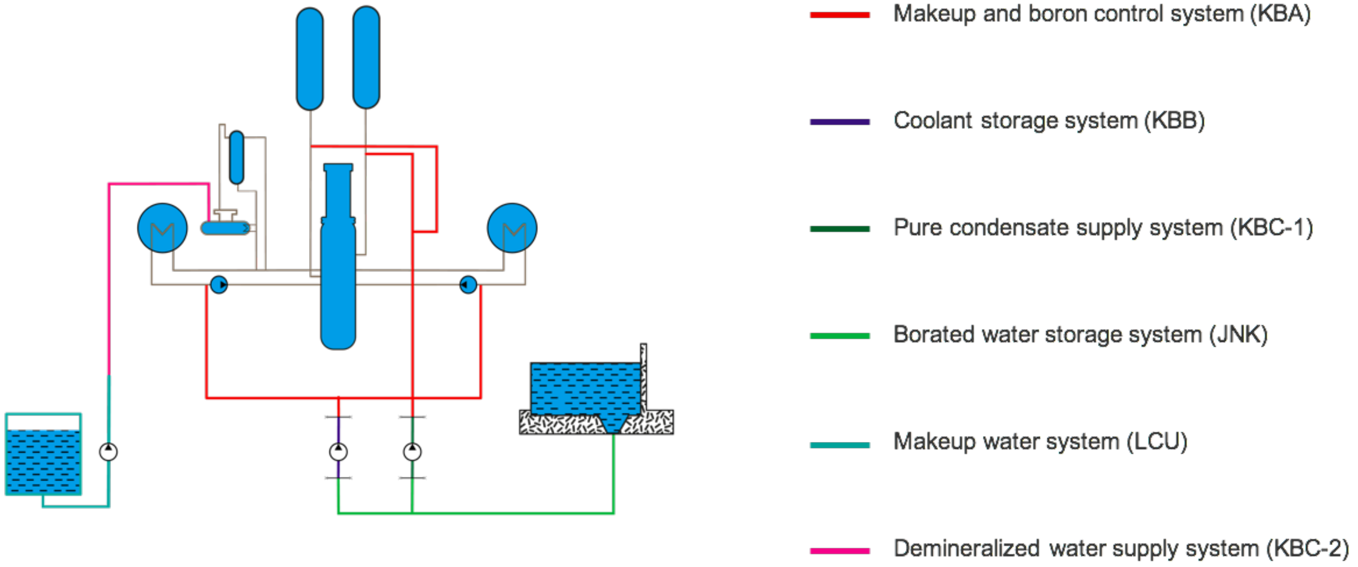

Makeup and boron control system (KBA)
Coolant storage system (KBB)
Pure condensate supply system (KBC-1)
Borated water storage system (JNK)
Makeup water system (LCU)
Demineralized water supply system (KBC-2)

Figure 4.2.1. *Schematic diagram of primary circuit filling.*

Before startup and any other activities, the primary circuit has to be filled with coolant. Makeup and boron control system (KBA) is used for this purpose. Coolant storage system (KBB) is a system where some amount of coolant is stored. Pure condensate supply system (KBC-1), borated water storage system (JNK), makeup water system (LCU), and demineralized water supply system (KBC-2) supply different combinations of coolant, water, boric acid, demineralized water, and pure condensate to the primary circuit to fill it. Different pumps are used for that—in general, pumps from the makeup water system (LCU) and coolant storage system (KBB).

Air removal from the reactor building equipment during the filling of the primary circuit

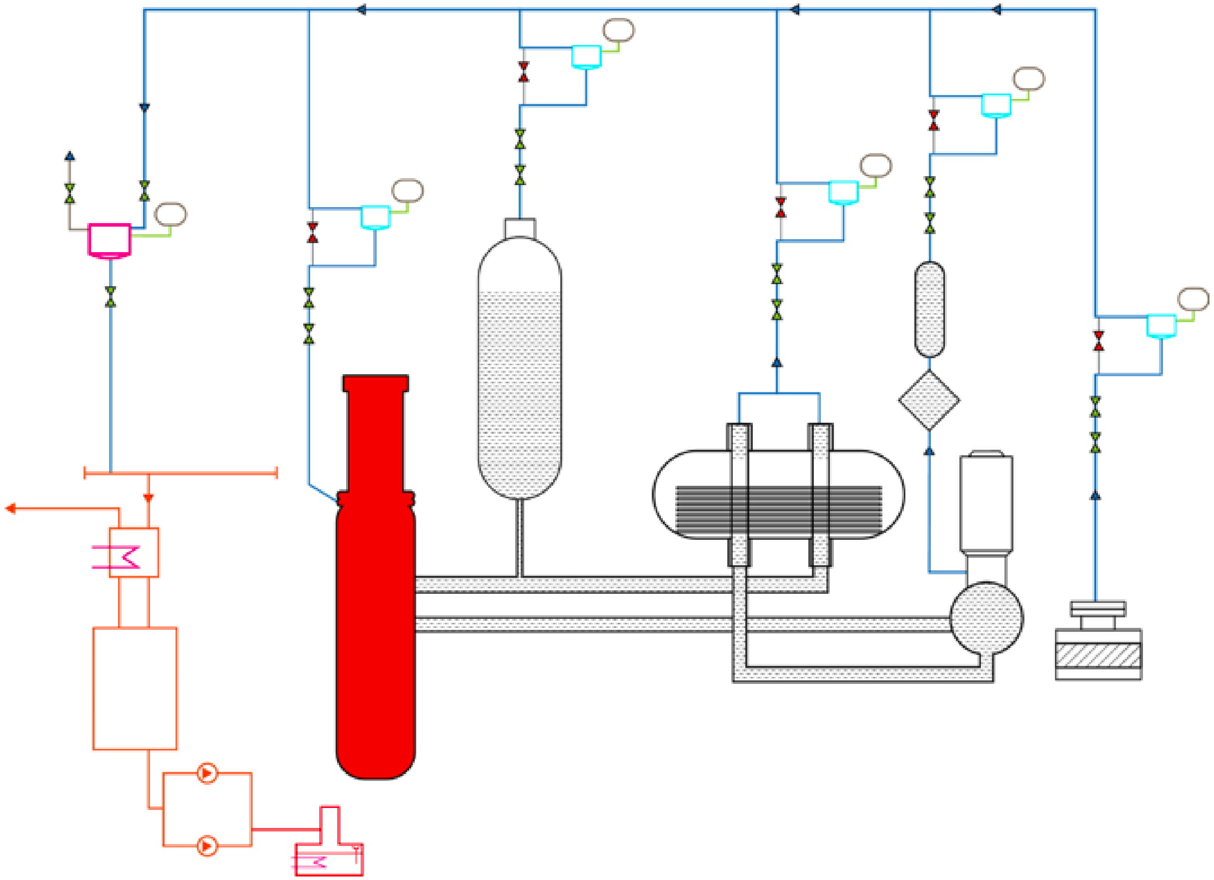


Figure 4.2.2. *Schematic diagram of air removal from the reactor building equipment during filling of the primary circle.*

As the primary circuit is closed, when coolant is added, the air from the corresponding part of the circuit has to be removed during the filling-up. There are venting lines on the top of main equipment of the primary circuit; on top of the reactor head, pressurizer, all steam generators, main circulation pumps, and on the relief tank, there are special air valves. The connection lines have sensors which are used for monitoring the level of water. When the air is removed from the primary circuit during filling-up, at some point the sensors signal that there is no air left—the equipment is fully filled. Having received the signal in the main control room, operators shut down filling-up of a particular part of equipment. The ventilation system is in operation during this mode, because high concentration of hydrogen should be prevented.

Air removal (Figure 4.2.2):

1. Valves on the air removal pipelines are opened (green color).

2. When water appears in the control tank (blue color), the valves are closed.

3. Air-water mixture enters the separation tank (purple color) and is separated as follows:

    a. air is blown off into the containment;

    b. water is routed to tank KTA.

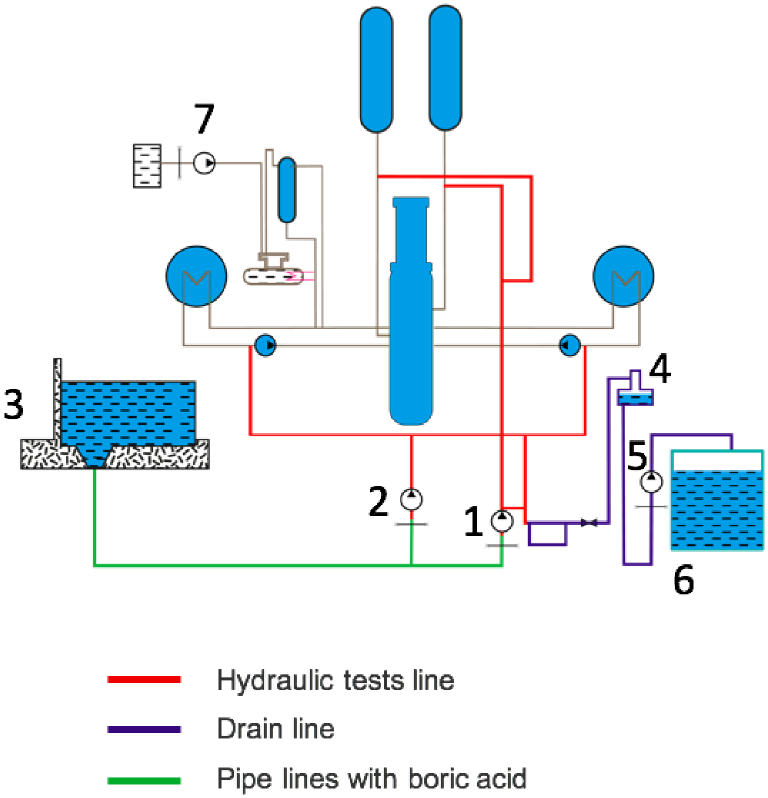


Figure 4.2.3. *Primary circuit hydraulic tests diagram, where 1 – hydraulic tests pump of the system (KBA), 2 – low capacity pump of the system (KBA), 3 – boron concentrate 16 g/dm3 storage tank of the system (JNK), 4 – deaerator of the system (KBA), 5 – coolant removal pump of the system (KBB), 6 – coolant storage tank of the system (KBB), 7 – portable pump and tank for HT performance.*

Primary circuit hydraulic testing

Based on a particular county's legislation, hydraulic tests should be arranged in timely manner, for example once a year or once every five years. However, hydraulic tests are obligatory before the NPP commissioning. These procedures ensure the airtightness of the primary circuit and the prevention of radioactivity release inside or outside.

Firstly, the pressure in the primary circuit should be established for heating-up. As mentioned in the third part of the course, nitrogen can be added in the pressurizer at 2 MPa for this purpose. After that, two main circulation pumps can be activated, and the primary circuit can be heated. Why is pressure needed to activate main circulation pumps? Because if the pressure is atmospheric and the main circulation pumps are activated, the coolant pressure in the suction line is low, which might lead to coolant boiling. As a result, there could be cavitation of coolant, and bubbles could implode against main circulation pump drives, which might damage them.

After establishing pressure, the primary circuit can be heated up for hydraulic tests. A special type of steel is used for the primary circuit. Cold steel can be used only in conditions of low pressure (less than 2 MPa). The temperature of steel is observed and if it is lower than the fracture appearance transition temperature, the pressure in the primary circuit must not be increased. It should be less than 2 MPa. For higher pressure, the primary circuit needs to be heated up. The target temperature depends on the primary circuit lifetime: when it is new, the temperature might not be so high, about 70 °C. During the operation, this temperature is increased gradually to 100-110 °C. That is why the temperature for hydraulic tests should be 135 °C—there has to be a gap for heating up of the primary circuit. As the primary circuit is heated up, steel is forced to take high pressure.

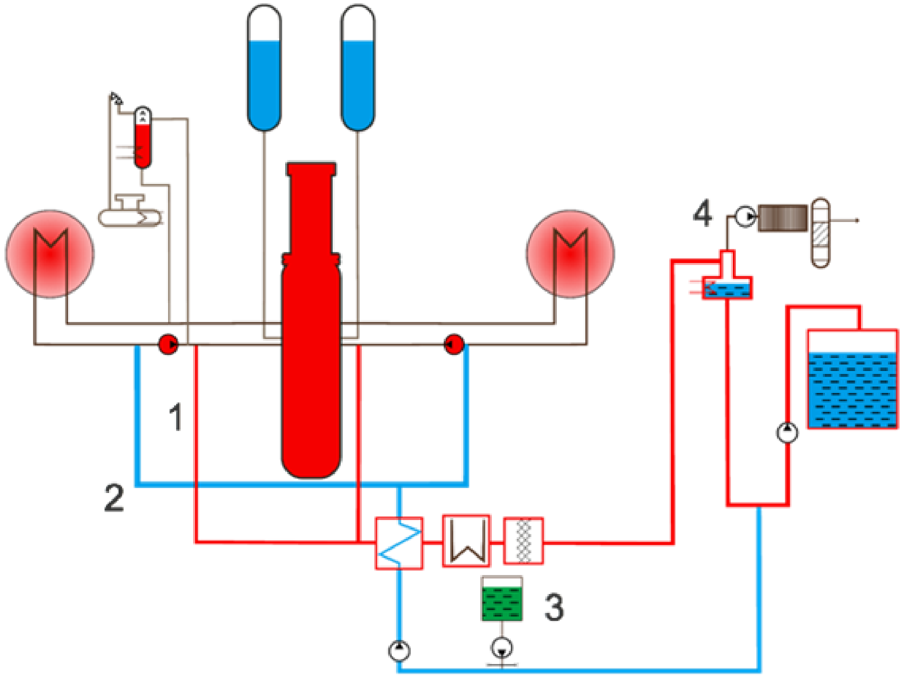


Figure 4.2.4. *Schematic diagram of the primary circuit heating-up, where 1 – blowdown line of the system (KBA), 2 – makeup line of the system (KBA), 3 – chemicals preparation and supply system for keeping primary coolant chemistry (KBD-1), 4 – hydrogen burning system (KPL1).*

After that, the makeup pumps in the KBA system can be activated and the pressure in the primary circuit can be steadily increased: first, up to 10 MPa, then up to 16.2 MPa for normal operation, then to 17.6 MPa, and at last to 24.5 MPa. The NPP should function at least for one hour during each of the first three steps. Everything that happens at each level is carefully monitored, especially for leakages. At the last level (24.5 MPa), the pressure is held for approximately 10 minutes. After that, the pressure is reduced to 19.6 MPa and all equipment is observed: the operator goes to the reactor containment to inspect the equipment and check for leakages. Naturally, there must be no leakage from the primary circuit.

Passive parts of the emergency core cooling system, e.g. relief tank, are included in the primary circuit but this equipment is tested independently with different parameters depending on the equipment requirements, which are less strict than the requirements for other equipment of the primary circuit.

Primary circuit heating-up

The next condition is the heating-up of the primary circuit. For heating-up, main circulation pumps are used. They are activated in the following way: the first one, then the opposite one, and after that any circulation pump could be activated. Four systems are used for heating-up and for control of this heating-up procedure: to fill the primary circuit, to remove and add coolant, to provide support of the primary circuit. Ventilation should be provided to remove oxygen, hydrogen, and radioactive gases from the primary circuit.

During the heating-up, the deaerator is activated. It is used to remove the gases: oxygen, hydrogen, and some others. To control the speed of heating-up, heat exchangers are activated. As a result, blowdown and makeup lines of the KBA system, chemicals preparation and supply system for keeping primary coolant chemistry

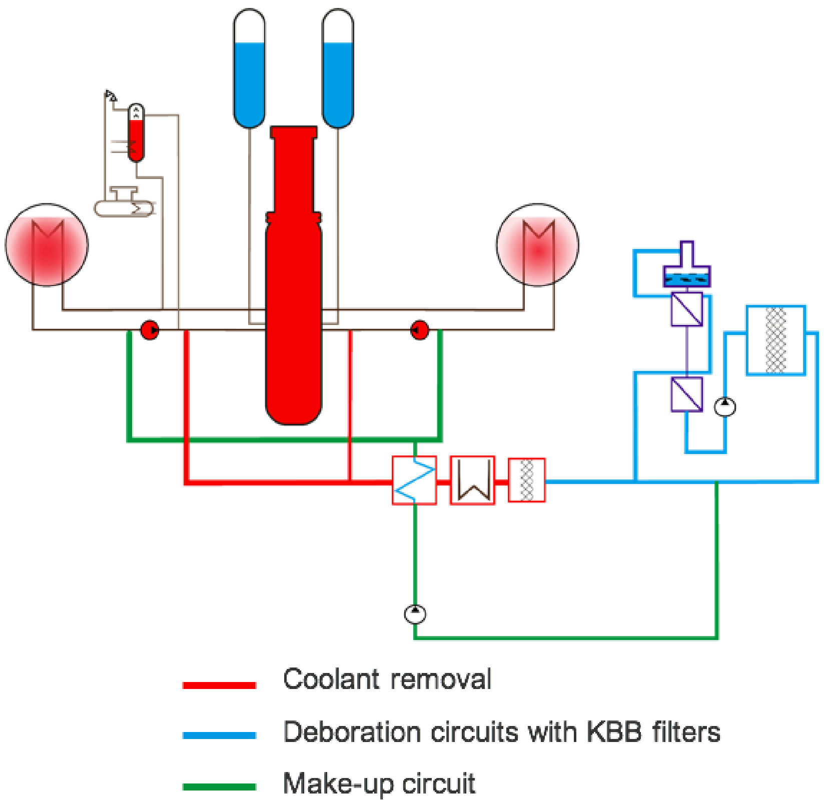


Figure 4.2.5. Steady state at the end of campaign.

(KBD-1), and hydrogen burning system (KPL1) are used for heating-up.

After that, pure condensate has to be added and the coolant has to be removed to KBB tank. It is possible to activate two different lines by the KBC-1 and KBA systems to add coolant to the primary circuit, and the KBB system—to remove coolant for storage in the tanks. At the startup, the concentration of boric acid is high. During the operation, this concentration is reduced steadily to a low level. At some point, it is close to zero—0.5-0.7 g/kg—which makes it difficult to remove. The KBB system can be used for this task. A lot of clean condensate is added to the primary circuit to remove as much boric acid as possible. As a result of activation of this system, the concentration of boric acid is reduced nearly to zero.

Control of leakage

All big equipment of the primary circuit has at least two seals with a small gap between them. There is a connection line with a sensor in this gap, which can be used to check if there is any coolant in the gaps between seals. For example, the seal line between a reactor vessel and a reactor head has two nickel seals. There is a connection pipe between them, with a sensor outside the reactor. If there is a leakage through the first seal, the gap between the seals is filled with coolant, and the sensor is activated. But the primary circuit is still airtight: only the first seal has leaked. A system is needed to control and monitor these leakages. The system is provided for many pieces of the primary circuit equipment: reactor, pressurizer, steam generator, main circulation pumps, and relief tank.

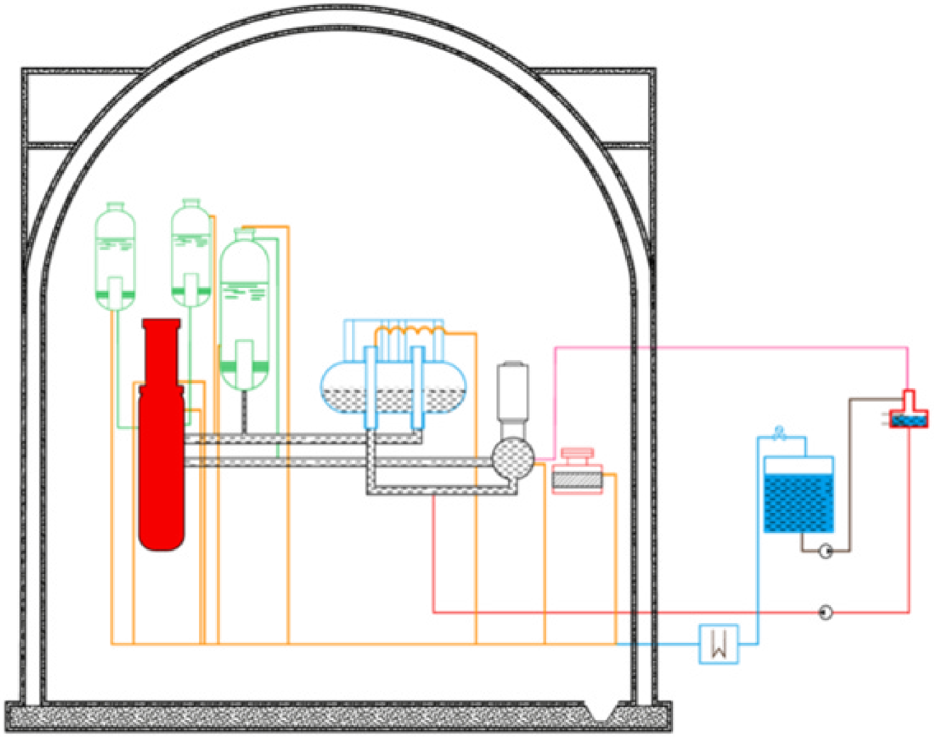


__Figure 4.2.6.__ Reactor Coolant Leakage Collection System (JET).

Reactor coolant leakage collection system (JET) should provide leakage monitoring of flange joints of the main RP equipment.

- Leaks are removed into the tank of the Reactor building equipment drainage system (KTA).
- Leaks collected in the tank are pumped into de-aerator of the Makeup and boron control system (KBA) and then returned into the circuit.
- Along with controlled leaks, RCP sealing water continuously returns into the primary circuit. Sealing water is supplied into KBA system de-aerator via RCP sealing water system (JEW) and then into the primary circuit (4 t/h).

Primary circuit cooling-down

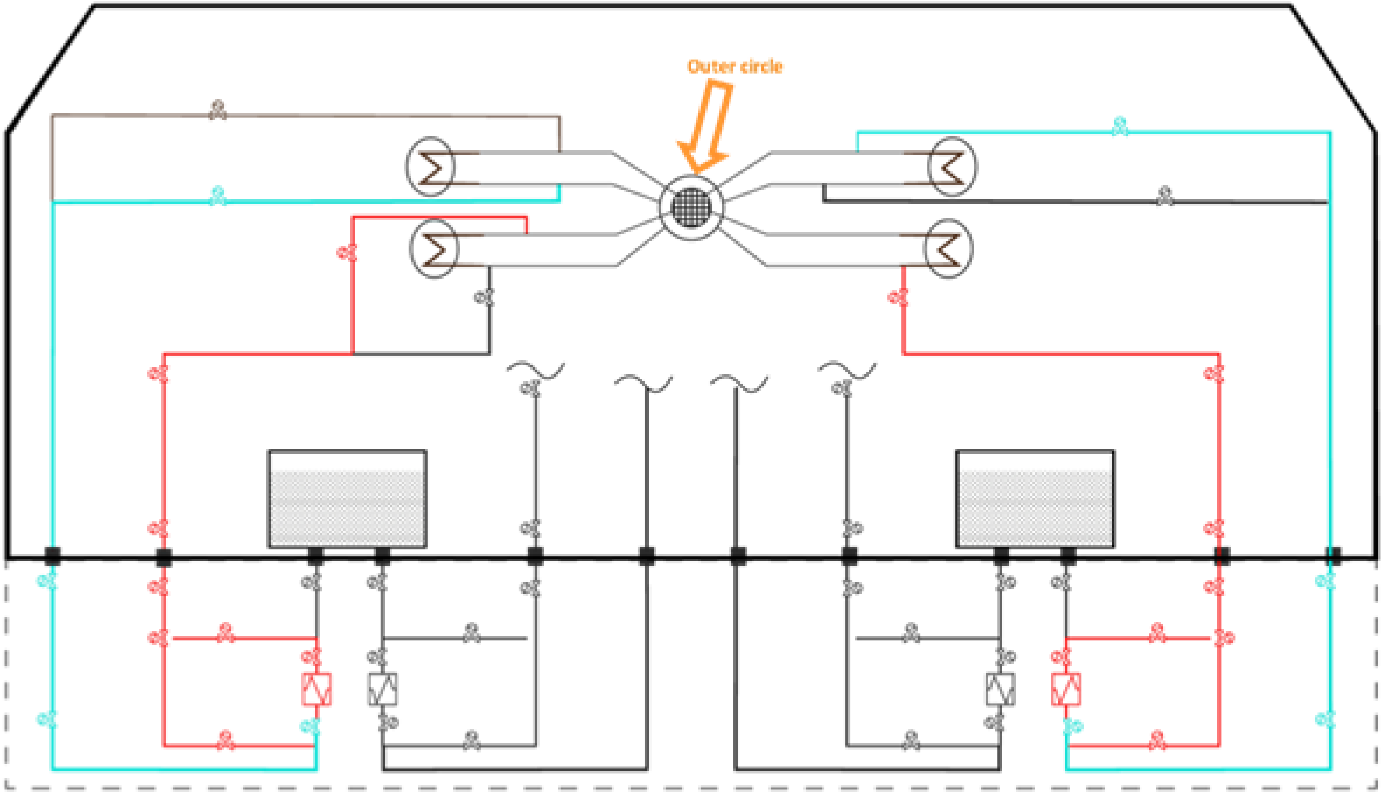


Figure 4.2.7. *Primary circuit cooling-down diagram.*

There are a lot of valves on the lines to control the speed of cooling-down, which is the main parameter which needs to be controlled during the process. The maximum speed of cooldown is based on legislation and particular requirements, but in general it is about 15 °C/h. As a result, after shutdown of the NPP 10-15 hours should pass to cool down the reactor before any further manipulation of the equipment.

Primary circuit drainage system

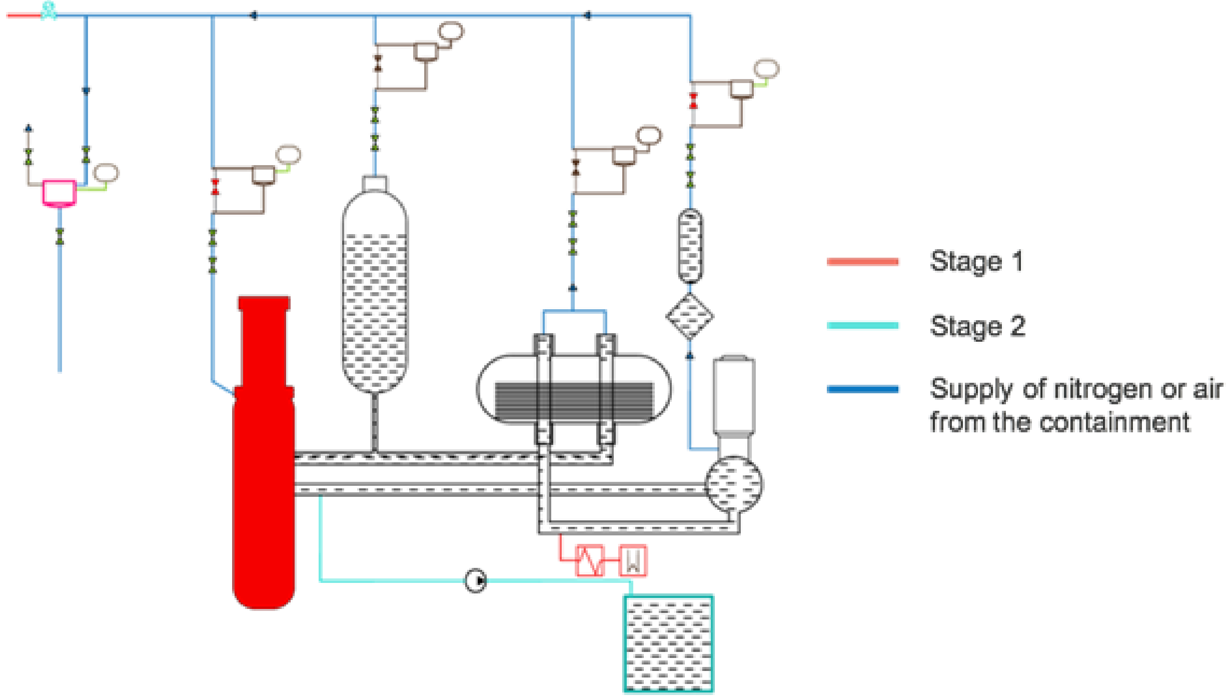


Figure 4.2.8. *Primary circuit drainage diagram.*
Nitrogen is supplied from Low pressure nitrogen system (KRK).

In general, there are two drainage lines, KBA and KBB. One of them is connected to inlet coolant lines, and the second—to outlet coolant lines. It is possible to drain the primary circuit down to the level of inlet nozzles in the reactor. There are no penetrations in the reactor vessel lower than the upper part of the reactor core, and there is no system designed to drain the reactor to a lower level. It is one more way to ensure inherent safety of the whole system.

Hydrogen blowing off from upper points of the reactor equipment

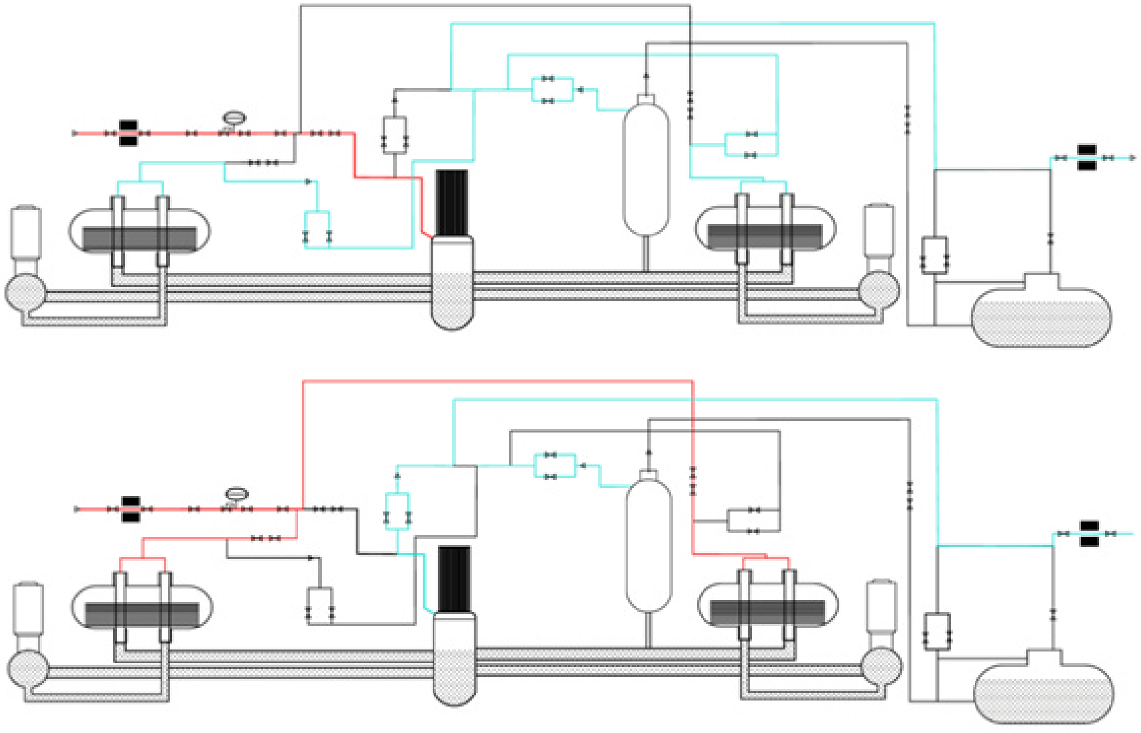
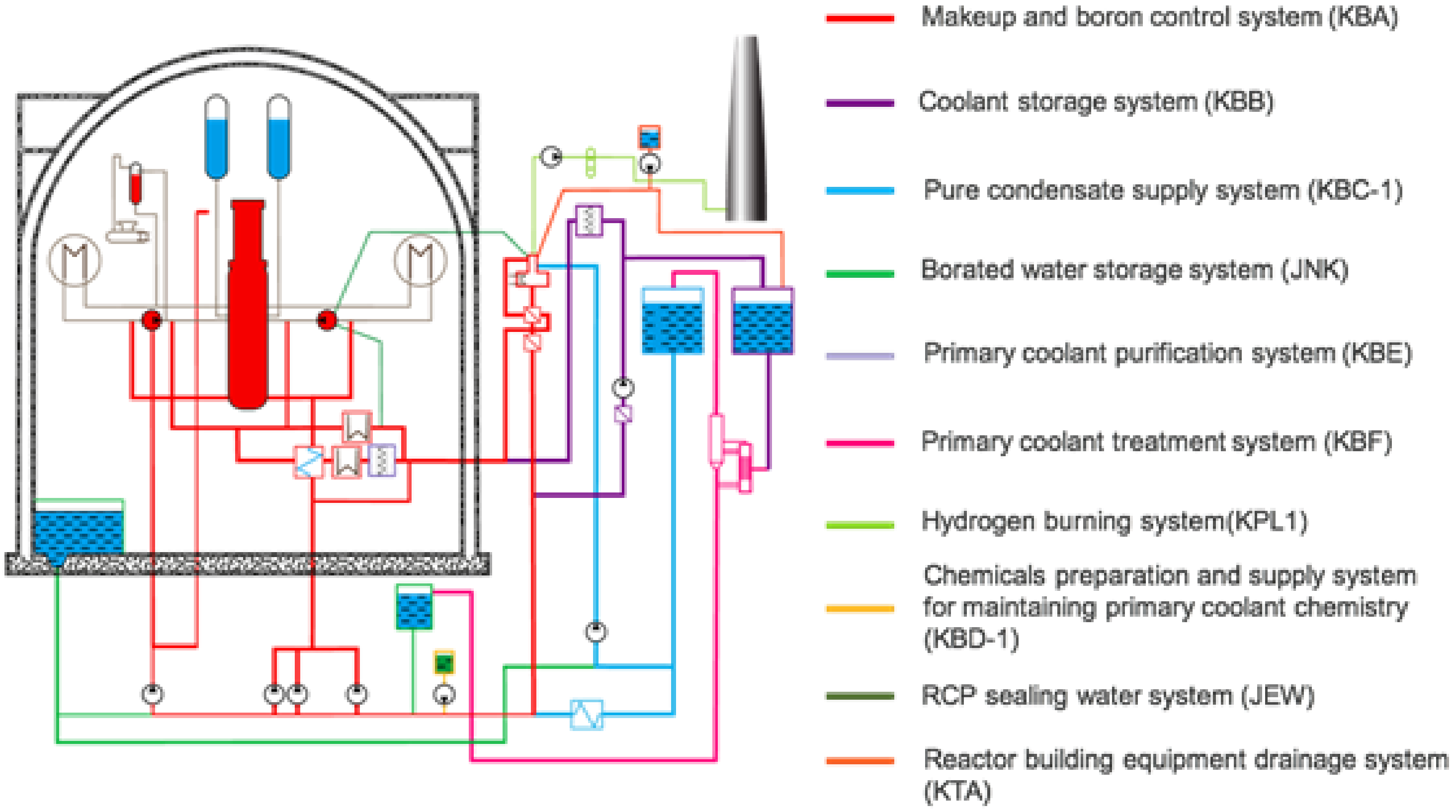


Figure 4.2.9. *Diagram of hydrogen blowing off from upper points of the reactor equipment.*

A good example of this phenomenon is as follows. Imagine a bottle of sparkling water: no gas could be seen inside; the bottle is filled with water, or some other liquid. But when the bottle is opened, a lot of gases are released. They could not be seen when the bottle was closed, but when it is opened, a lot of them are produced. A similar process occurs in NPPs. During the operation at nominal level of power, the coolant is in liquid state; when the pressure in the primary circuit is reduced, a lot of gases are produced. One of them—hydrogen—is a very dangerous gas. There is a lot of hydrogen in the primary circuit to compensate for the injection of boric acid. As a result, a system for blowing off hydrogen is needed. At the top points of all pieces of equipment, there are venting valves which are connected to the hydrogen burning system. Passive hydrogen recombiners belong to this system.

General arrangement of auxiliary systems interacting with the primary circuit


Makeup and boron control system (KBA)
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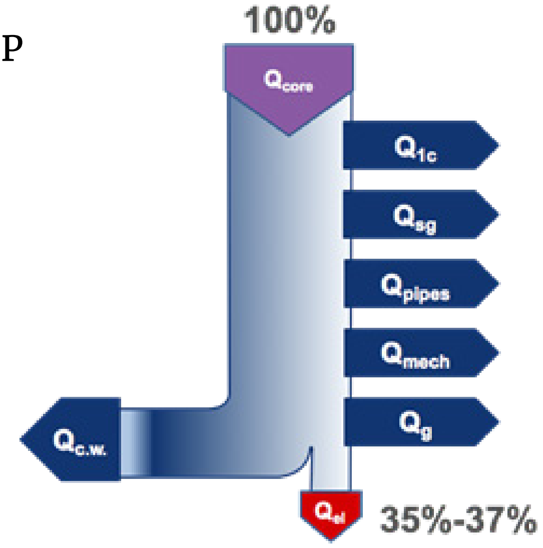
Primary coolant treatment system (KBF)
Hydrogen burning system(KPL1)
Chemicals preparation and supply system for maintaining primary coolant chemistry (KBD-1)
RCP sealing water system (JEW)
Reactor building equipment drainage system (KTA)

Figure 4.2.10. *General arrangement of auxiliary systems interacting with the primary circuit.*

Figure 4.2.10 presents the general arrangement of auxiliary systems and connection of these systems to the primary circuit. Some of these systems are located inside the containment; they should be protected. And some of them are located outside the containment in the auxiliary building.

4.3. *Turbine island*

Thermal balance of NPP



Q_{core} – core thermal power
Q_{1c} – power losses in primary circuit
Q_{sg} – power losses in steam generators
Q_{pipes} – power losses in pipelines (steamlines)
Q_{mech} – mechanical losses
Q_{g} – power losses in generator
Q_{el} – power used for electricity production
Q_{cw} – power losses in condenser cooling water

Figure 4.3.1. *Thermal balance of NPP.*

Thermal capacity of the reactor core is about 3,200 MW. However, only 1,200 MW are produced by the electricity generator; 2,000 MW are lost somewhere. The efficiency of NPP is about 35-37% depending on operation modes. The reason and the place of the loss should be well understood.

The main source of the loss is the condenser in the secondary circuit. It is a huge piece of equipment which is used for cooling-down of coolant after the steam turbine on the suction line of feedwater pumps. The number of these condensers depends on the number of low-pressure cylinders: for example, it could range from 1 to 5 depending on the design of the NPP turbine island. Cold water from the sea, cooling towers, or other source is used for cooling down the condenser—this is the place where NPP is heating up the environment.

The main source of pollution during NPP operation is the heat which has to be removed in condensers. For this reason, some NPPs have gardens or farms, which, for example, produce vegetables or fish. The Kalinin NPP in the northern regions of Russia has short experience in producing tropical fish. The Olkiluoto NPP in Finland has experience in producing grapes on site. It is possible to use the heat for heating up the soil, building farms and producing food in cold climates.

The other types of energy loss are:

- In the primary circuit: there is resistance in the circulation lines; the primary circuit is heated up and then cooled down; the air inside the reactor containment needs to be cooled down during the operation.
- In steam generators: it is not possible to produce all 800 MW that are put into a steam generator. The loss is the result of the difference in temperature between inlet and outlet.
- In pipelines (steamlines): e.g. there is friction loss during the transportation of steam from the steam generator to the turbine.
- Mechanical losses: the losses from mechanical power in mechanisms like main circulation pumps and feedwater pumps.
- In electrical generator: losses for active power and reactivity power.
- Power used for electricity production: power has to be provided for e.g. electrically driven pumps and electrical heaters in the pressurizer. The main circulation pump has power capacity of about 6 MW, so 24 MW of electrical power for four MCPs are needed at all time.

To summarize, efficiency of NPP is reduced and in general can be approximately 35-37% from inlet to outlet.

Turbine cycle

Different processes can be identified during the operation of the steam turbine:

- 1-2: adiabatic expansion in turbine;
- 2-3: steam condensation in the condenser;
- 3-4: pumped from low to high pressure;
- 4-5: heating of coolant in steam generator up to saturation temperature;
- 5-1: steam production in steam generator.
- $\eta = Q_1 / Q_2$

The efficiency of a steam turbine is measured by the ratio of Q_1 to Q_2. This is an ideal cycle; in reality, moisture reheaters, separators, and additional equipment are used to increase the efficiency of the turbine cycle.

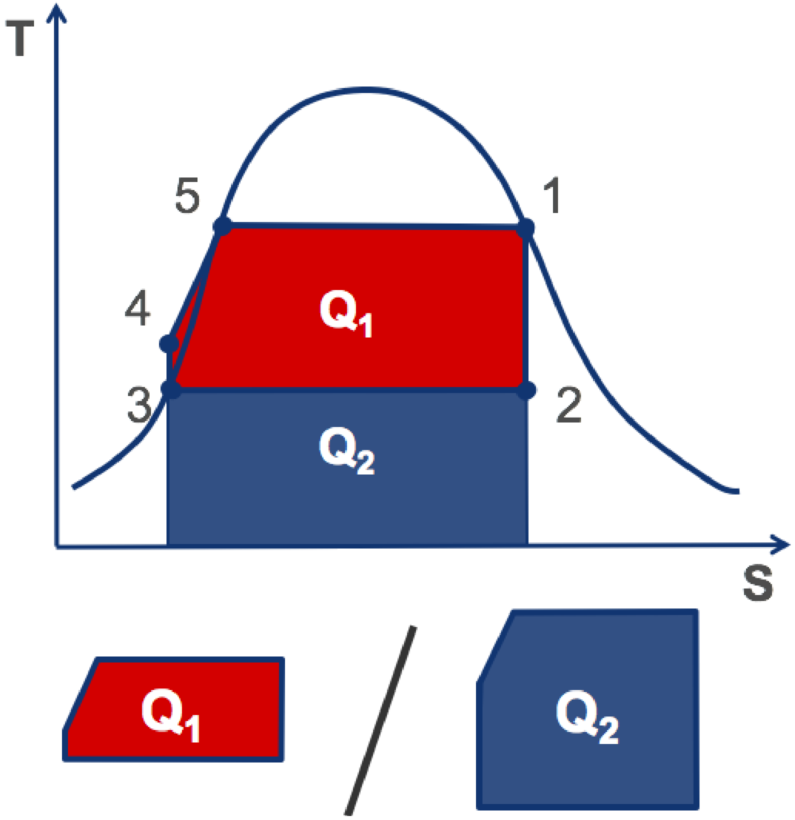


Figure 4.3.2. *Turbine cycle.*

Components of the steam turbine plant

Steam turbines for NPPs are generally similar to steam turbines for other types of power plants, such as coal power plants. Main differences are in details. For example, the level of radioactivity needs to be monitored in steam lines to control leakage from the primary and secondary circuits. Different effects of reactivity need to be considered. For example, if the power in the generator is changed, the power in steam generators and the power of the reactor are changed, which affects reactivity. But generally, similar steam turbines are used for different power plants, including NPPs.

Main parts of steam turbine plant include:

- steam turbine with turbine control system, shaft turner, and steam distribution valves;
- condenser with intake-discharge devices, supports, and valves;
- oil lubrication and governing systems; equipment of vacuum system and turbine sealing system;
- equipment of vacuum system and turbine sealing system;
- equipment of intermediate steam separation and superheating system;
- regeneration system equipment;
- steam, condensate, water, and oil lines.

Basic parameters of steam turbine plant

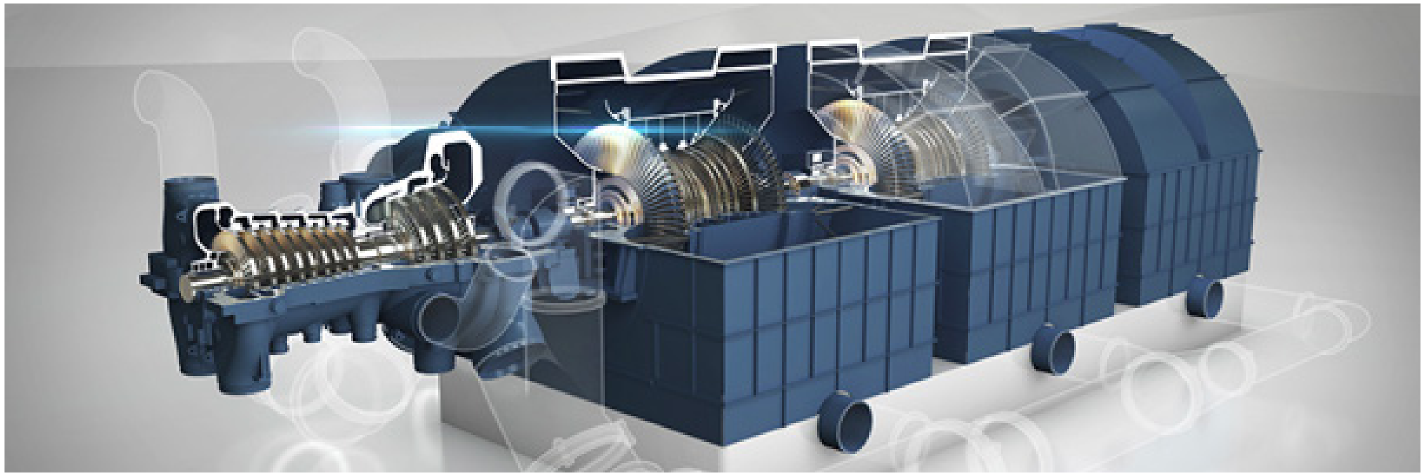


Figure 4.3.3. *Basic parameters of steam turbine.*
Source: dieselgasturbine.com/wp-content/uploads/2016/09/Arabelle-nuclear-turbine-overview-cgi.jpg

Without the generator, the length of a turbine is 51.8 m, with generator—68.8 m. Its total weight is about 2,500 tonnes. Rotation speed for a low-speed turbine is 1,500 rotations per minute (rpm). A big rectangular building is necessary to contain a turbine, of planned size 62 m × 125 m, which is approximately equal to a football field. There are several levels: the elevation of the lowest is about -10 m, the roof level is +39 m high; the difference between them is about 50 m, while the width is 60 m and length is 125 m.

Location of the turbine building

- The turbine building is rectangular in plan. Dimensions of the building in plan are 62.0 m x 124.9 m.
- The building has two underground floors with floor elevations -10.00 m and -3.60 m and two above-ground floors with floor elevations +4.90 m and +14.60 m. The elevation of the roof truss bottom is +39.00 m. Main operating elevation for maintenance of the turbine set is +14.60 m. Additional floors in the area of oil facilities are arranged at elevation +8.55 m.
- The reactor building is positioned in the extension line of the turbine shaft, thereby avoiding risk of turbine missiles consequences.

Processes in steam turbine plant

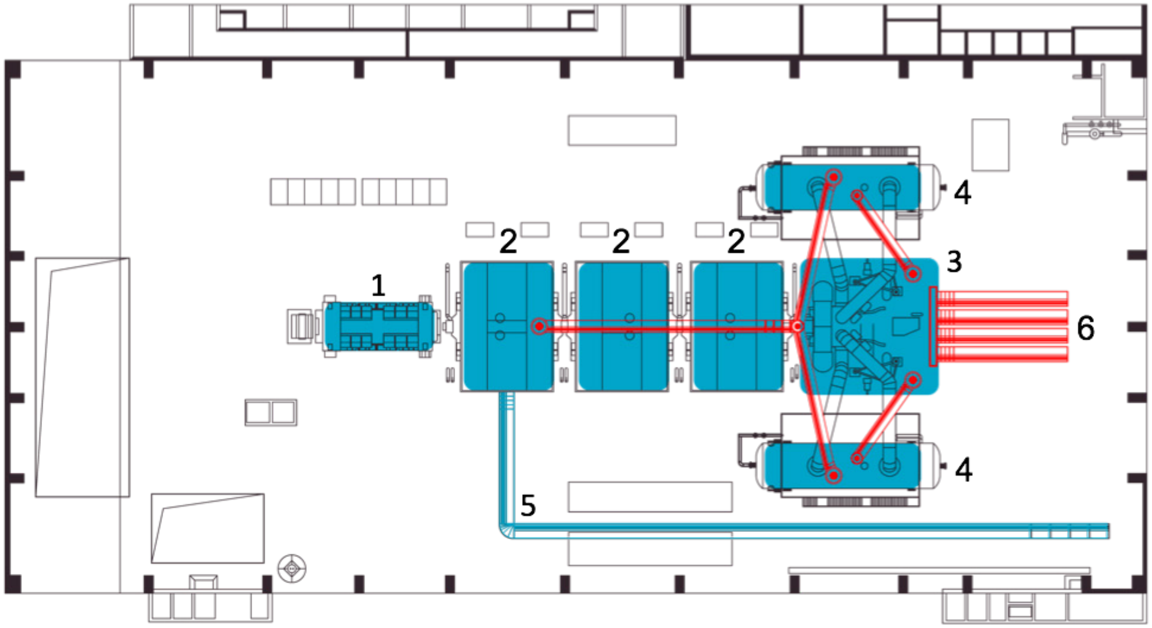


Figure 4.3.4. *Turbine building, where 1 – generator, 2 – low-pressure turbine, 3 – high-pressure / intermediate-pressure turbine, 4 – moisture separators-reheaters, 5 – cooling / heating and preparation, 6 – steam from steam generators.*

Steam comes from four steam generators (6 in Figure 4.3.4) to high pressure cylindrical turbine (3). Some steam comes directly to moisture separators-reheaters (4). The first part, which comes to the high-pressure turbine, rotates this turbine and also goes to the moisture separators-reheaters after that. There, the steam is reheated again and transferred to the intermediate-pressure turbine, which is in one configuration with the high-pressure turbine. After the steam has lost a lot of temperature and power, it needs to be reheated again and is transferred to the low-pressure cylinders (2). For Arabelle turbine plants, three low pressure cylinders are used. Each is connected to a condenser; cooled down and converted to liquid state, the steam goes through the suction line to feedwater pumps and is pumped back to the steam generators.

In general, the process is very simple. However, many additional systems are involved in details, such as the coolant preparation, where all gases which are produced when the pressure is reduced need to be removed. In steam generator the pressure is high, in condenser it is extremely low, so large deaerators are needed to remove resulting gases. There are treatment systems for coolant cleaning procedures and other additional systems.

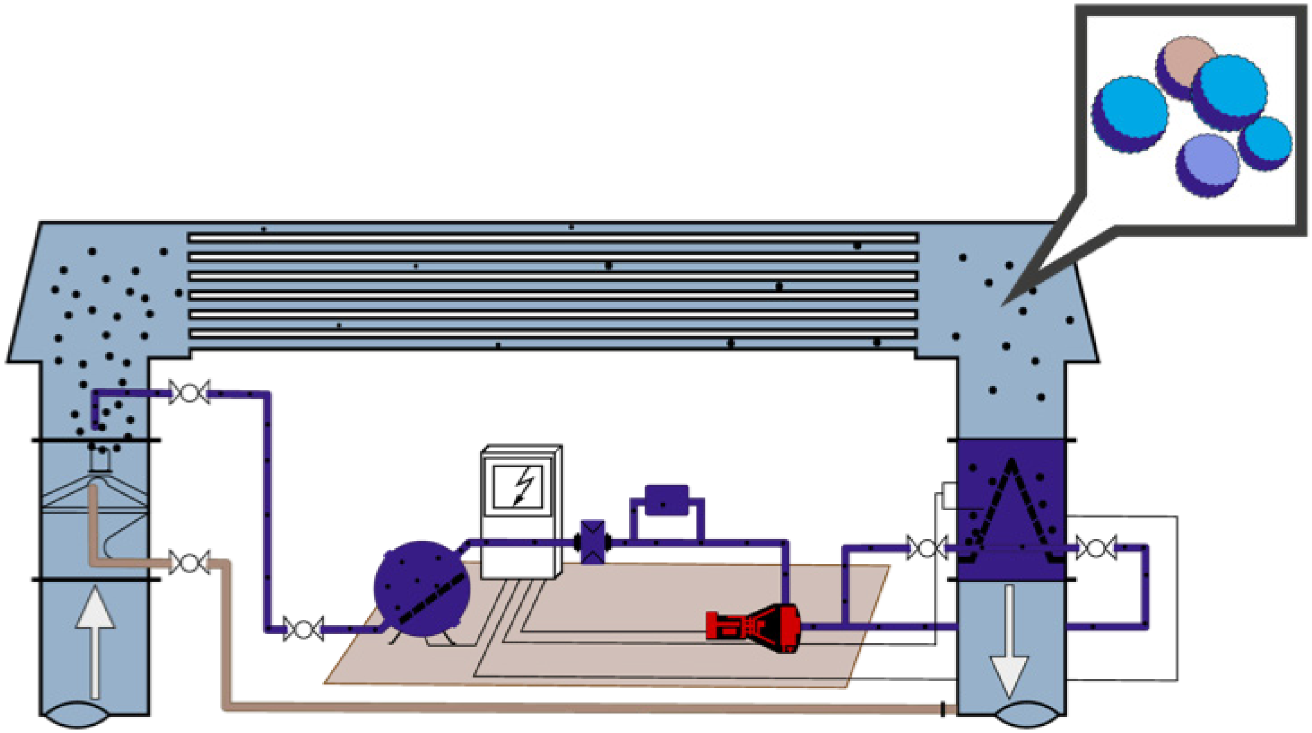


Figure 4.3.5. *Ball cleaning system.*

If water from outside of an NPP is used in the condenser, a lot of rust can be produced inside as a result. Seawater, for example, is very dangerous in terms of corrosion. For this reason, a ball cleaning system is used to clean the condenser. The system is shown in Figure 4.3.5. Soft balls are distributed in the system, pumped through the condenser, cleaning it on their way, and removed in the end.

4.4. *Handling of spent nuclear fuel*

Refueling machine

The last section of this part of the course concerns handling of the spent fuel on NPP. A special refueling machine is designed for AES-2006 which is used for handling:

- fuel assemblies (FAs);
- control rods of the control and protection system (CPS);
- CPS AR (absorbing rod of control and protection system) bundles and frames for CPS AR;
- leak-tight bottles;
- bottle plugs;
- bottle plugs of the failed fuel assemblies detection system (FFDS);
- leak-tightness control of fuel elements of FAs in the main mast by means of the fuel element cladding tightness monitoring system.

The refueling machine consists of the bridge, trolley, telescopic main mast, and TV rod with lighting (as illustrated in Figure 4.1.1). It works in automatic mode and has a lot of protection sensors to ensure it is working properly.

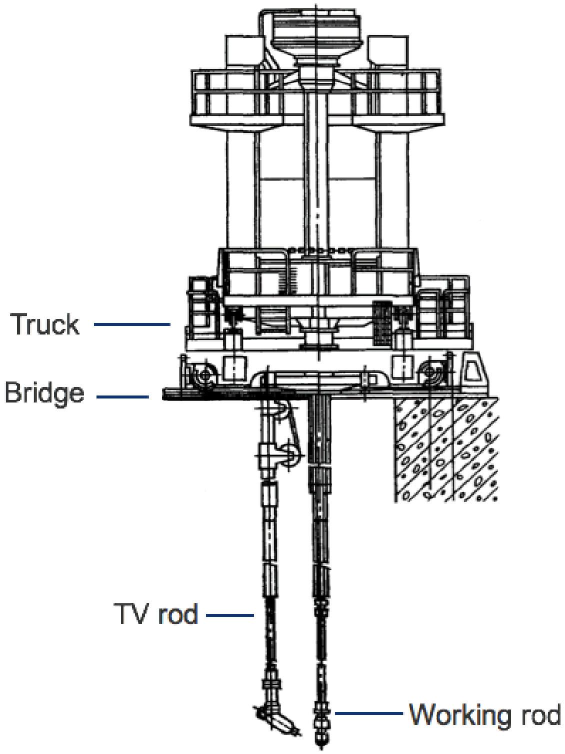
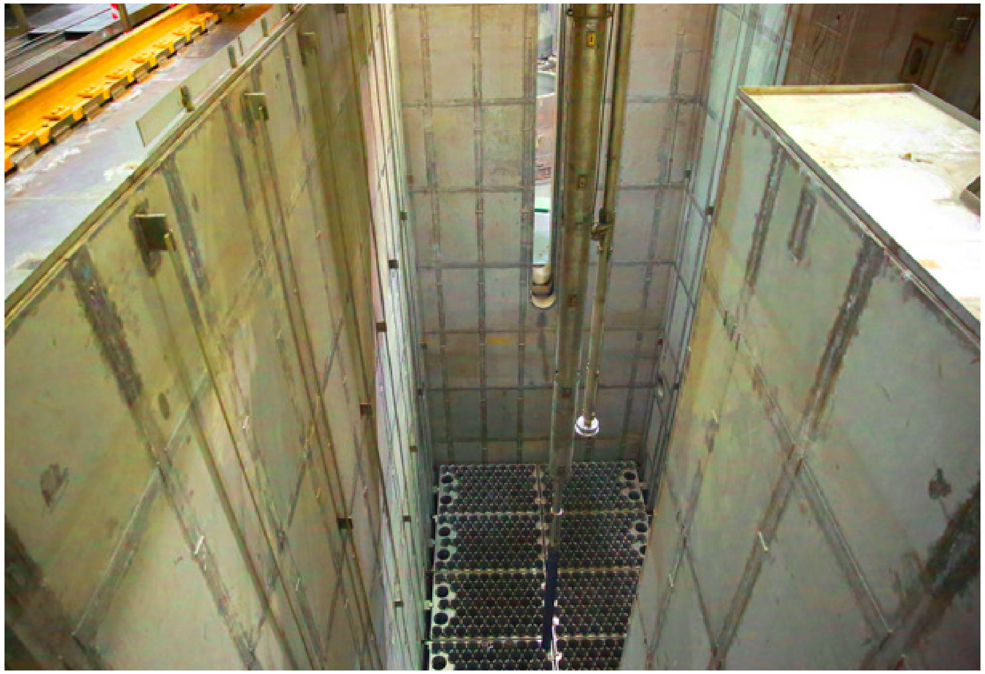


Figure 4.4.1. *Refueling machine. Source: leg.co.ua/arhiv/generaciya/atomnye-elektricheskie-stancii-i-ih-oborudovanie-28.html.*

Generally, there are fixing elements on the tops of fuel assemblies. At the end of the telescopic mast of the refueling machine, there is a corresponding fixing element which can be used to move a fuel assembly. All fuel assemblies have identification numbers; a particular FA can be chosen using a system which controls the refueling machine, placed to another area inside the reactor core, or sent to the spent fuel pool.



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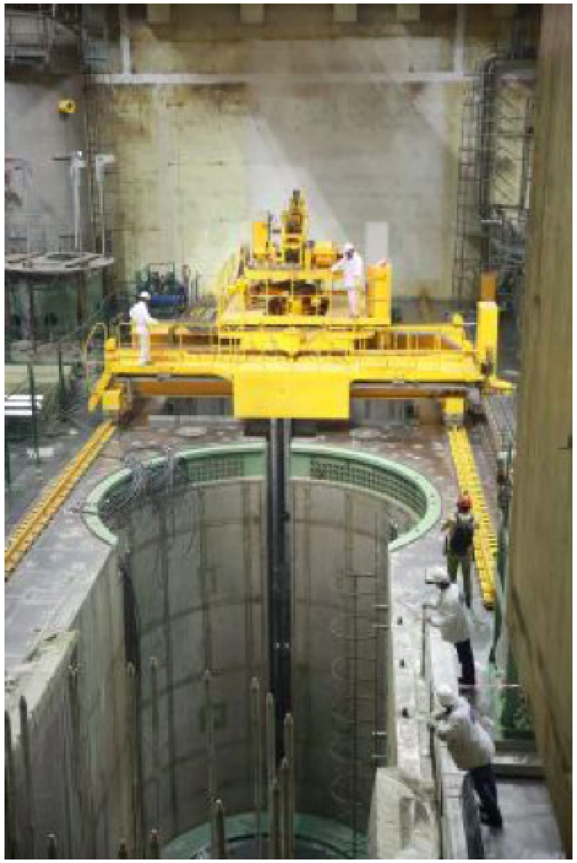

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Figure 4.4.2. *Refueling machine.*

The spent fuel pool is connected directly to the VVER reactor pit; during the refueling, the reactor pit and the reactor must be fully filled with water to ensure the refueling procedure is conducted underwater.

Storage of spent nuclear fuel

The number of places in the spent fuel pool and its general dimensions are designed for the following functions:

- placement of spent fuel discharged from the reactor during reloading procedure;
- placement of damaged fuel assemblies and fuel rods;
- storage of spent fuel before transportation from the reactor containment;
- residual heat removal from the spent fuel pool;
- providing biological protection of personnel from fuel stored in the pool.

According to the calculations, it is possible to swim in the upper level of the spent fuel pool. The high level of water in the upper part of the spent fuel pool provides biological protection for people who stay inside the containment during reloading procedures, maintenance works, etc. The exposure from the spent fuel assemblies is not high.

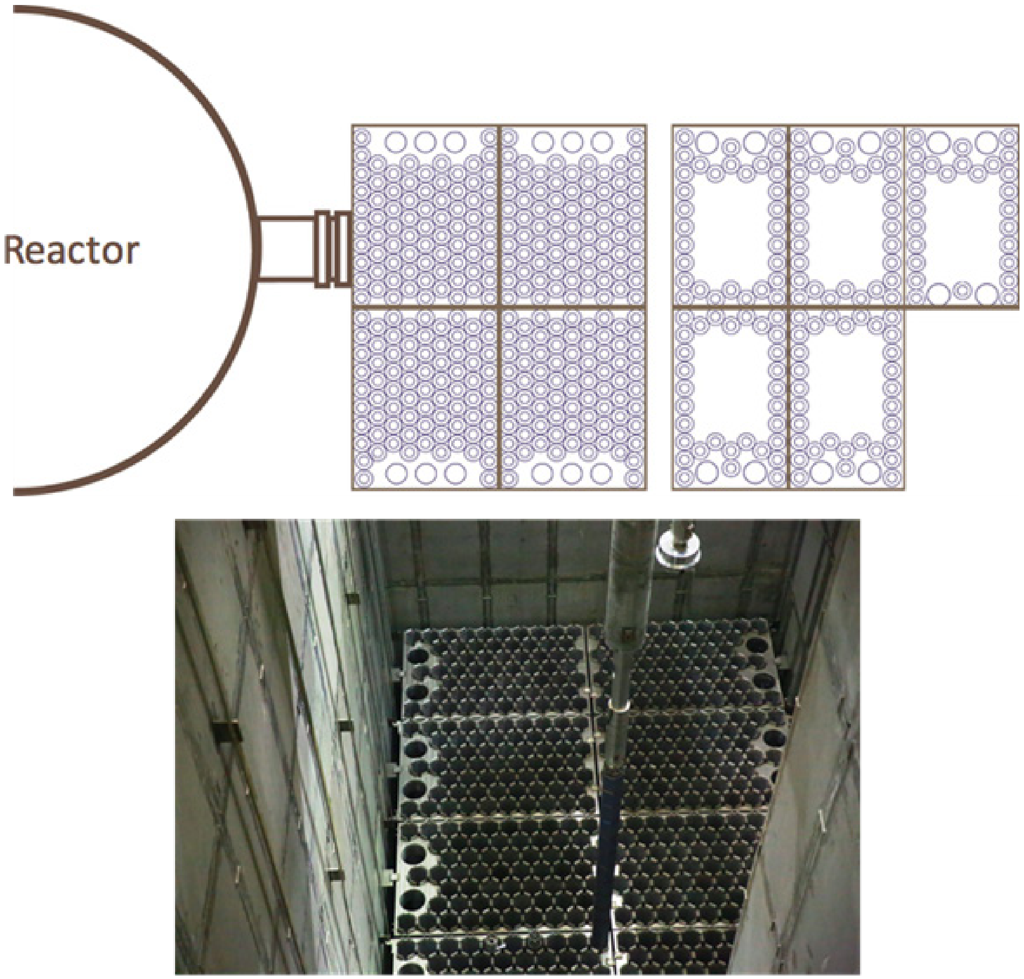

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Figure 4.4.3. *Storage of spent nuclear fuel.*

Capacity of the spent fuel pool

There are generally two spent fuel pools in one containment, placed on one line. Their total capacity is 603 places for fuel assemblies. The calculation for this number is as follows: firstly, places for fuel assemblies are necessary. As mentioned before, there are 163 fuel assemblies in the reactor core. During particular occurrences, free space is needed to remove all fuel from the reactor core to the spent fuel pool. Which means that out of 603, 163 are needed for the reactor core assemblies. After reloading, residual heat from the used fuel has to subside—which means the spent fuel has to stay in the pool for 3-5 years. Depending on the fuel cycle, 5 years of operation require from 163 up to 250 FA places. Additionally, approximately 100 places are necessary to have space for maintenance and repair.

In section 1 of the spent fuel pool, there are 304 cells for fuel assemblies and 12 cells for transport packages. Transport packages are tanks for spent fuel pool which can be used to transport spent fuel to reprocessing factory, repository, or long-term storage. Section 2 has about 299 cells for fuel assemblies and additional 12 cells for transport packages.

Capacity of the spent fuel pool is designed for seven years of fuel assemblies storage including possibility of repair of every section. Spent fuel pool is divided in two sections by a 600 mm thick wall. Water coolant supply and removal system is provided in every section. The necessary amount of detectors is placed for monitoring what is happening in the spent fuel pool and measuring parameters in every section. Leakage control system is provided, which works for the whole depth of the pool and under every section of shelf stand. The resulting system can be used for VVER cooldown and for cooldown of the spent fuel pool, to prevent situations with abnormal heating of fuel assemblies and for ensuring the safety.

To summarize, three topics are discussed in the fourth part of the course: the reactor auxiliary system, turbine island, and fuel handling, which provide resources for understanding the normal operation of VVER and occupational aspects of VVER reactors.